THE CHEMISTRY OF THE STARS IN RELATION TO TEMPERATURE.[1]

THE recent advances in our knowledge which have come from the combination and interaction of solar, stellar and laboratory research, carried on by the aid of instruments of much greater power than those formerly used, have given us a firm chemical hold on all the groups of stars in my classification of them. These groups were established by discussing sequences of lines before the origin of the lines had been made out. A series of hieroglyphics is now replaced by chemical facts; and we can now study the chemistry of the stars, as well as their order in a system of classification.

The first question which naturally arises is this: Do the chemical elements make themselves visible indiscriminately in all the celestial bodies, so that practically, from a chemical point of view, the bodies appear to us of similar chemical constitution? This is not so.

From the spectra of those stars which resemble the sun, in that they consist of an interior nucleus surrounded by an atmosphere which absorbs the light of the nucleus, and which therefore we study by means of this absorption, it is to be gathered that the atmospheres of some stars are chiefly gaseous, *i.e.* consisting of elements we recognise as gases here, of others chiefly metallic, of others again mainly composed of carbon or compounds of carbon.

Here then we have spectroscopically revealed the fact that there is considerable variation in the chemical constituents which visibly build up the stellar atmospheres.

This, though a general, is still an isolated statement. Can we connect it with another?

By means of one of the first principles of spectrum analysis we know that the hotter a thing is, the light of which produces a continuous spectrum, the further does the spectrum stretch into the violet and ultra-violet.

Hence the hotter a star is, the further does its complete or *continuous* spectrum lengthen out towards the ultra-violet, and, *caeteris paribus*, the less is it absorbed by cooler vapours in its atmosphere.

Now to deal with three of the main groups of stars, we find the following very general result:—

Gaseous stars ...	... Longest spectrum.
Metallic stars ...	... Medium spectrum,
Carbon stars ...	... Shortest spectrum.

We have now associated two different series of phenomena, and we are entitled to make the following general statement:—

Gaseous stars ...	... Highest temperature.
Metallic stars ...	... Medium temperature.
Carbon stars ...	... Lowest temperature.

Hence the differences in apparent chemical constitutions are associated with differences of temperature.

This, then, is the result of our first inquiry into the existence of the various chemical elements in the atmospheres of stars generally. We get a great diversity, and we know that this diversity accompanies changes of temperature. We also find that the sun, which we independently know to be a cooling star, and Arcturus, are identical chemically.

I next pass from the general to the particular, and give the detailed results recently obtained in the case of stars as hot or hotter than Arcturus—taking Arcturus to represent the solar temperature.

In a paper on the "Chemistry of the Hottest Stars,"[2] in 1897, I stated the results so far arrived at concerning the order in which certain spectral lines appeared, and others disappeared, in stars arranged in a series of ascending temperatures.

Since that paper was written many important advances have been made, among them I may mention the following:

Proto-metals.

With regard to the metals, the recent work on the enhanced lines in the spectrum of metals, α Cygni[1] and the sun's chromosphere enables us to deal with the lines observed at the highest temperature in the spectra of the following substances: magnesium, calcium, iron, manganese, nickel, chromium, titanium, copper, vanadium, strontium, silicium.

The accompanying untouched reproductions of photographs will show the wonderful similarity which exists between these three spectra.

As we have to deal both with the arc and spark lines of these substances, for the sake of clearness I call the latter "*proto-metallic*" lines, and consider the substances which produce them, obtained at the highest available laboratory temperatures, "proto-metals," that is, a finer form of the metal than that which produces the arc lines, corresponding to the "meta-elements" imagined by Crookes.

The temperature ranges of the enhanced lines of these metals have been investigated in various stars with the following results:—

Metal.	Range of temperature (upward series).	Range of temperature (downward series).
Magnesium	α Ursæ Min. to γ Argûs	α Eridani to Procyon
Calcium ...	α Tauri to γ Argûs	α Eridani to Arcturus
Iron ...	α Tauri to ζ Tauri	β Persei to Arcturus
Titanium...	α Tauri to ζ Tauri	β Persei to Arcturus
Manganese	α Ursæ Min. to α Cygni	β Persei to Procyon
Nickel ...	α Ursæ Min. to α Cygni	β Persei to Procyon
Chromium	α Ursæ Min. to α Cygni	γ Lyræ to Procyon
Vanadium	α Ursæ Min. to α Cygni	Sirius to Procyon
Copper ...	α Ursæ Min. to α Cygni	β Persei to Procyon
Strontium	α Tauri to α Cygni	Sirius to Arcturus

I pointed out in the note referred to that the enhanced lines of the above substances seemed to account for almost all of the more marked lines in α Cygni. It is on this ground that I have investigated their behaviour in other stars before waiting for the results of the complete inquiry. Another reason has been that, although in addition to the enhanced lines of the metals shown in the foregoing table, those of barium, cadmium, molybdenum, lanthanum, antimony, lead, palladium, tantalum, erbium and yttrium, tungsten, cerium, uranium, cobalt and bismuth have already been investigated with lower dispersion, and a spark obtained with the use of a much less jar capacity, so far I have no certainty that any of these substances exist in the reversing layers of stars of intermediate temperature.

The temperature ranges of the arc lines of some of the metals have also been investigated, and the results are shown in the following table:—

Metal.	Range of temperature (upward series).	Range of temperature (downward series).
Iron ...	α Tauri to α Cygni	α Canis Majoris to Arcturus
Calcium ...	α Tauri to α Ursæ Min.	α Canis Majoris to Arcturus
Manganese	α Tauri to α Ursæ Min.	α Canis Majoris to Arcturus

So much, then, for the metals. I now turn to the gases.

Proto-hydrogen.

Some little time ago Prof. Pickering, of Harvard Observatory, found on examining the spectra of the southern stars, that one of them on the poop of the ship which forms the constellation Argo, hence called ζ Puppis, contained a system of lines not hitherto recognised, and he naturally concluded that it indicated a new element.[1] On further inquiry he found reason to suppose that this new series was in some way connected with hydrogen, since the lines occupied the same positions as those computed from the same formula and constants from which the ordinary series of hydrogen was calculated, the only difference in the employment of the formula being that even values of *n* were used instead of odd values.

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[1] This article embodies a paper read at the Royal Society on Thursday, February 23.

[2] *Proc. Roy. Soc.*, vol. lxi. p. 148.

[1] NATURE, February 9 (p. 342).

Profs. Pickering and Kayser both concede that this new form of hydrogen is due most probably to a high temperature, and Prof. Kayser expressly states "that this series has never been observed before can perhaps be explained by insufficient temperature in our Geissler tubes and most of the stars."

If, as suggested both by Prof. Kayser and myself, this new series and the one previously known are probably of the subordinate type, the principal series of hydrogen is still beyond our ken, unless indeed one of the still "unknown" lines represents it, as suggested by Prof. Rydberg. Another possibility is that, even in the hottest stars so far considered, the temperature is not high enough to allow its molecule to exist uncombined.

On the view that the new series of probable hydrogen lines in ζ Puppis represents the effect of a transcendental temperature, an attempt has been made to produce this spectrum in the laboratory. In the high-tension spark in hydrogen at atmospheric pressure the ordinary series of hydrogen lines is very broad. The use of the spark with large jars in vacuum tubes results in the partial fusion of the glass and the appearance of lines which have been traced to silicium, but the new series has not yet been observed.

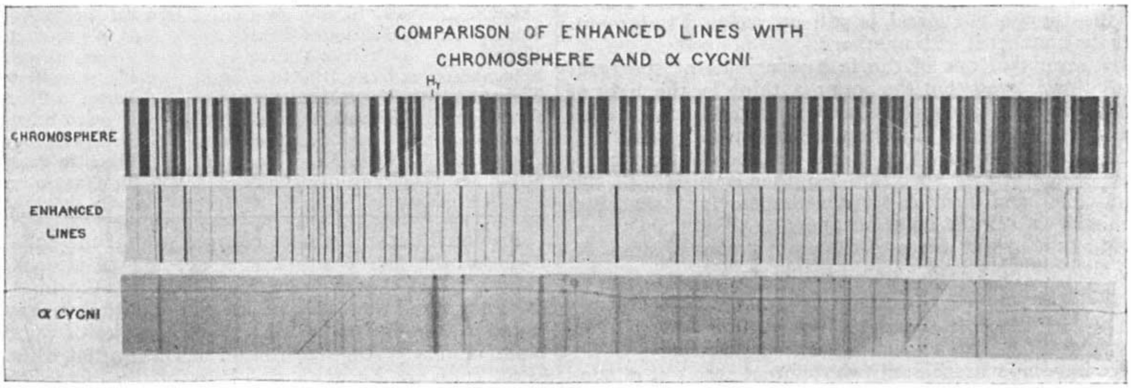

Fig. 1.

In his first communication, Prof. Pickering mentions lines at 4698, 4652, 4620, and 4505, but he does not refer to them in his second paper, which has special reference to the new series. The line 4505 was at first taken to be one of the components of the new series, but this seems to have been subsequently superseded by the employment of the line about 4544, which agrees better both as regards intensity and the calculated position 4543·6.

As this new hydrogen series seems to bear the same relation to the well-known one as the proto-metallic lines bear to the metallic, I call the gas which produces it proto-hydrogen for the sake of clearness.

The new series of lines discovered by Prof. Pickering has been found in the spectra of ζ, ε, δ and κ Orionis photographed at Kensington in 1892.

Prof. Pickering himself has since found this system of lines in other stars than ζ Puppis, and Mr. McClean, in his admirable work on the brightest stars of the southern hemisphere, has obtained photographs of the spectrum of γ Argûs, and on which the new series appears.

From a discussion of these stars in relation to the others photographed, there can be little doubt that we are here face to face with the very hottest stars so far known, and that the new series of hydrogen lines represents one among the last stages of chemical simplification so far within our ken.

We are, therefore, now in a better position to determine the relation of this new gas to other gases, both known and unknown, appearing in stars of nearly equal temperature.

Other New Gas Lines.

But even with our present knowledge of stellar spectra we find that in relation to the hottest stars there are still some gaps in our chemical knowledge; not only is this so, but have we any right to assume, taking into account the limitations of our means of observation and of the strict limitation of our observations to the relatively small part of space nearest us, enormous though it is, that we are as yet really in touch with the highest stellar temperatures?

Again, we cannot be certain that the small number of stars as yet studied puts us in presence of the highest stellar temperatures. Those stars which apparently are at the very apex of the temperature curve are involved in unknown lines, and require a special study.

Two typical unknown lines have wave-lengths at 4089·2 and 4649·2,[1] and besides these three other unknown lines occur in γ Argûs.

As these most probably reveal still undiscovered gases, I include them in the following table showing the limits

Origin.	λ of chief lines.	Range in ascending series of stars.	Range in descending series of stars.
Unknown.	4457 4451 3876	Seen only in γ Argûs.	
Hydrogen (New).	4544·0 4200·4	ζ Orionis to γ Argûs.	No stars available.
Unknown.	4089·2	α Crucis to ζ Orionis.	
Unknown.	4649·2	,,	α Eridani.
Helium.	4471·6 4026·3	Rigel to γ Argûs.	α Eridani to γ Lyræ.
Asterium.	4388 4009	Rigel to γ Argûs.	α Eridani to γ Lyræ.
Hydrogen.	Complete Series.	Aldebaran to γ Argûs.	α Eridani to Arcturus.

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[1] See *Astrophysical Journal*, iv. p. 369, and v. p. 95.

[1] *Proc. Roy. Soc.*, vol. lxii. p. 52.

of stellar temperature to which the various known and unknown lines, probably of gaseous origin, extend.

Mr. McClean has stated that certain of the oxygen lines (amongst which is the strong triplet at λλ 4070·1, 4072·4 and 4076·3) appear in the spectrum of β Crucis and other stars of nearly equal temperature. My own observations, so far as they have gone, tend to confirm this view; but other photographs and more laboratory work are needed to explain certain changes of intensity which have been observed. The lines attributed by Mr. McClean to oxygen have been noted between α Crucis and ζ Orionis in the upward series, and in stars at about the α Eridani stage of temperature in the downward series.

There is evidence that the strongest lines of nitrogen at λ 3995·2 and λ 4630·9 make their appearance in stars at about the temperature of α Crucis. These lines appear from Rigel to ζ Orionis in the upward series, and are present in the stars at the α Eridani stage in the downward.

I pointed out many years ago[1] that at high temperatures the flutings of carbon in the violet are replaced by a line at λ4267·5. There is a line at this wavelength in the spectra of stars ranging in temperature from that of Rigel to ζ Orionis on the up side, and from α Eridani to β Persei on the down side of the temperature curve.

There is no known line of gases or metals to which this line can be assigned. It is probable, therefore, that carbon exists in stars of the same temperature as that at which oxygen and nitrogen have been traced.

Two lines in the spectrum of Silicium (λ4128·5 and λ4131·5) have been traced in stars between the temperatures of α Ursæ Min. and α Crucis in the upward series, and between those of α Eridani and Procyon on the downward.

The accompanying map shows the facts relating to stars as hot as, or hotter than, the sun, as we know them at present.

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[1] *Proc. Roy. Soc.*, vol. xxx. p. 461.

Description of Map.

The map is arranged on the following plan. The temperature of the sun and Arcturus forms the lowest stage. The upper limit is defined by γ Argûs, the hottest star so far known. On the left the stars named are those of increasing temperature, on the right those of decreasing temperature. Those on the same horizon represent equal mean temperatures so far as the cleveite gas and enhanced lines help us to determine them. The blank spaces indicate that so far no star has been photographed in the spectrum of which the enhanced lines exactly match those on the opposite side.

The names of the various chemical substances included in the discussion are given at the top. I have retained the prefix "proto" to that condition of each metallic vapour which gives us the enhanced lines alone, and I have added it to that form of hydrogen seen only in the hottest stars.

The behaviour of the most typical line of each chemical substance is indicated by a double line looped at the top at its highest range. The length and varying thickness of the lines in stars on both sides of the temperature curve are derived from the observed appearance and intensity of the lines, noted in the different stars.

The wave-lengths of the lines discussed are shown at the bottom of the map.

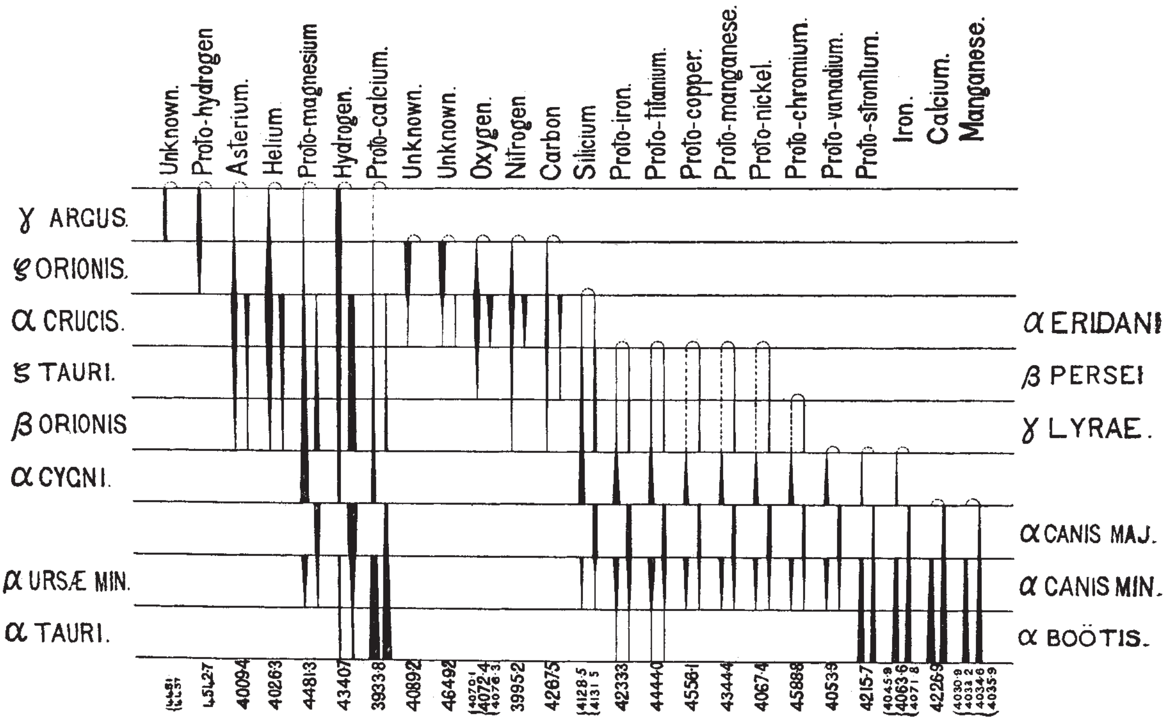

FIG. 2.

Details of Changes observed.

The facts embodied in the map present to us the spectral changes noted in stars of Groups III., IV. and V. of my classification,[1] and are a result of a more general inquiry than those referred to in my previous papers,[2] the origins of a very considerable number of stellar lines having since then been traced to enhanced lines of metals and to known gases.

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[1] *Proc. Roy. Soc.*, vol, xliii. p. 117 (1887).

[2] *Proc. Roy. Soc*, vol. xliv. p. 1 (1888); *ibid.*, vol. xlv. p. 380 (1889); *Phil. Trans.*, 184A, 1893, p. 725.

It will be seen that this more general inquiry entirely justifies the prior statement[1] that the metallic lines are thickest in stars increasing their temperature, and the hydrogen lines thickest in stars decreasing their temperature, in other words, on the opposite arms of the temperature curve. I have already stated a possible explanation.[2]

It will be observed that, so far, I have not been able to find stellar spectra on the downward side corresponding to those of γ Argus and ζ Orionis; but it is more than probable that near the apex of the curve only a small change, will be observed; their default, therefore, is of less consequence than it might have been.

The same remark applies to α Cygni and Sirius; but here it is certain that the differences in the relative intensities of the gaseous and enhanced lines will be considerable, judging from what happens above and below the heat stages represented by them.

The stars used in the discussion give us very definite results, showing that the various chemical forms are introduced at six very distinct heat levels.

The Temperature Ranges.

I next proceed to make some remarks upon the series of facts now for the first time brought together; it must, however, be borne in mind that all the chemical elements and all parts of the spectrum have not yet been included in the survey.

(1) Hydrogen appears throughout both series of stars from top to bottom. Proto-magnesium and proto-calcium follow suit very nearly; but the highest intensity of the former is reached at the stage represented by α Cygni, and of the latter at the solar temperature represented by α Tauri and Arcturus.

(2) With the above exceptions all the chemical forms so far traced are relatively short-lived.

This is the first important differentiation. In the light of (1) we are justified in assuming that the substances in (2) would be visible in the stellar reversing layers if they were there.

(3) In the stars of higher temperatures we deal generally with gases. Below the stages represented by β Orionis and γ Lyræ we deal with proto-metals and metals, hydrogen being the only exception.

(4) The proto-metals make their appearance at about the same heat-level at which the gases (with carbon), always excepting hydrogen, begin to die out.

This is the second important differentiation. It is interesting to notice the distinct difference of behaviour of carbon and silicium in the descending series; the former goes through the same stages as oxygen and nitrogen, the latter behaves like the proto-metals.

(5) With the exception of iron the metals, as contradistinguished from the proto-metals, only make their appearance in stars at and below the heat-level of Sirius.

This is the third important differentiation. It is accompanied with a notable *diminution* of hydrogen and proto-magnesium, and with an *increase* of proto-calcium; indeed, the latter seems generally to vary inversely with the hydrogen.

In all these changes we seem to be brought into presence of successive polymerisations due to reduction of temperature. Of the origin of proto-magnesium and proto-calcium the stars as yet tell us nothing; but it is difficult to believe that the earliest forms of the other metals are not built up of some of the constituents of the heat ranges represented by those between γ Argus and α Crucis.

The question arises whether the order of visibility at reduced temperatures now indicated does not explain the absence of proto-hydrogen, oxygen, and nitrogen from the spectra of the sun and nebulæ; the metals present in, and the absence of quartz from, meteorites, and the similarity of the gaseous products obtained from meteorites and metals, native and other, in vacuo at high temperatures.

Norman Lockyer.

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[1] *Proc. Roy. Soc.*, vol. lxi. p, 182.

[2] *Proc. Roy. Soc.*, vol. lxi. p. 183.

THE INSTINCTS OF WASPS AS A PROBLEM IN EVOLUTION.[1]

THIS work has been looked forward to with the deepest interest by all naturalists who are familiar with Dr. and Mrs. Peckham's observations upon the courtship of the spiders, and who were aware that this long-continued and laborious research had been undertaken by them. The observations and conclusions of M. Fabre upon the instincts of the solitary wasps have been so often quoted, and have formed the foundation of so large a superstructure of theory, that it became of the highest importance that they should be repeated by other naturalists. The late George Romanes and many other writers on evolution have always looked upon these observations as the strongest of all arguments for a Lamarckian instead of a Darwinian interpretation of instinct. Thus Romanes wrote in "Mental Evolution in Animals": "Several species of the Hymenoptera display what I think may be justly deemed the most remarkable instincts in the world. These consist in stinging spiders, insects, and caterpillars in their chief nerve centres, in consequence of which the victims are not killed outright, but rendered motionless; they are then conveyed to a burrow previously formed by the *Sphex*, and, continuing to live in their paralysed condition for several weeks, are at last available as food for the larvæ when they are hatched. Of course the extraordinary fact which stands to be explained is that of the precise anatomical, not to say physiological knowledge, which appears to be displayed by the insect in stinging only the nerve centres of its prey" (quoted by the authors on pp. 221, 222). A still more imaginative description is also quoted (on pp. 220, 221) from Eimer, who says: "This is one of the most marvellous instincts that exist; since the wasp operates on various larvæ with nervous systems of various forms, she must effect the paralysis in various ways, and even apart from this, she makes a physiological experiment which is far in advance of the knowledge of man. . . . It may be suggested that the wasp only paralysed the larvæ in order to carry them more easily; but even if this were the case, she must, since she now invariably acts in this way, have drawn a conclusion by deductive reasoning. In this case it is absolutely impossible that the animal has arrived at its habit otherwise than by reflection upon the facts of experience." The authors truly say of these remarks, and the rest of the quotation from Eimer: "One can hardly be expected to take such statements seriously, since it is certain that the writer has no knowledge of the life-histories of these insects." Eimer and Romanes were both quoting from Fabre, and, relying upon his inferences even more fully than upon his observations, they both held that a Lamarckian interpretation is inevitable. Such instincts, they maintained, can only have arisen by the inheritance of the results of intelligent observation. In order thoroughly to test the foundation upon which such far-reaching conclusions have been built, Dr. and Mrs. Peckham have carefully observed all the species of solitary wasps which they could find in their beautiful summer home, with Dr. C. A. Leuthstrom, on Pine Lake, Wisconsin. As in the case of other insect orders, these Hymenoptera have a wonderfully familiar look to an

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[1] "On the Instincts and Habits of the Solitary Wasps." By George W. Peckham and Elizabeth G. Peckham. Wisconsin Geological and Natural History Survey. *Bulletin* No. 2. Scientific Series No. 1. (Madison, Wis.: published by the State, 1898.)